NASA's In-Space Manufacturing Project: Materials and Manufacturing Process Development Update

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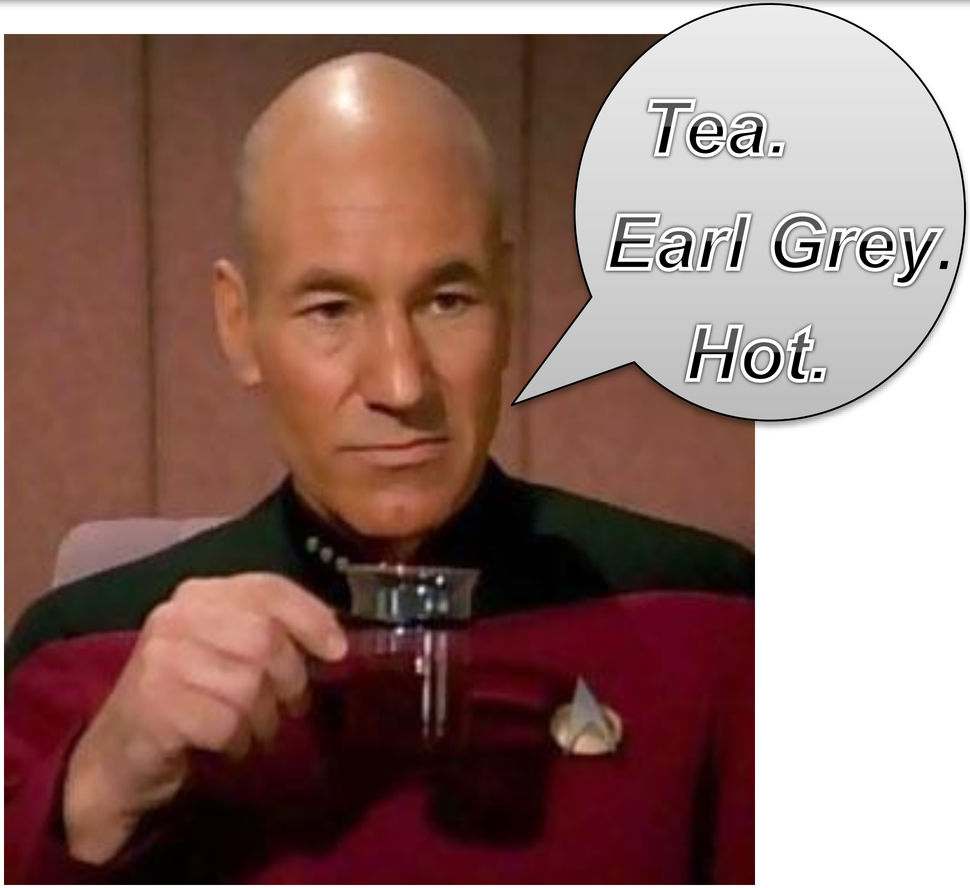
In-Space Manufacturing (ISM)



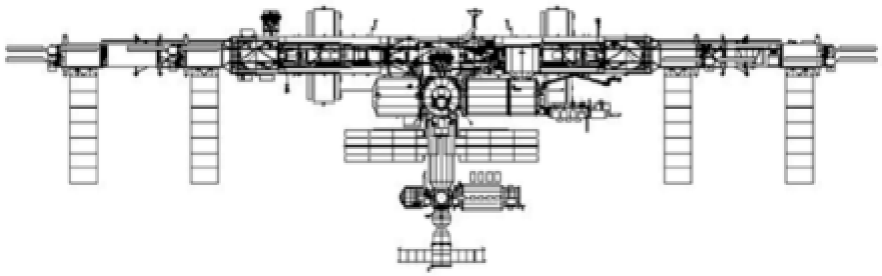
"If what you're doing is not seen by some people as science fiction, it's probably not transformative enough."
-Sergey Brin

The Current Paradigm: ISS Logistics Model

Each square represents 1000 kg

Total Approx. Spares Mass Currently On-Orbit = 13,170 kg

Mass estimates are for mass of spare item only - do not including any packaging or carrier mass



~3,000 kg Upmass per year

Predicted Annual Average Upmass 2012-2020

Corrective Maintenance	*= 1,260 kg*
Preventive Maint. / Consumables	*= 1,930 kg*
Total	*= 3,190 kg*

Expected Average Annual Failures = 450 kg*

Total Approx. Spares Mass Currently Stored On Ground = 17,990 kg

~18,000 kg on ground, ready to fly on demand

This is for a system with:
- **Regular resupply (~3 months)**
- **Quick abort capability**
- **Extensive ground support and redesign/re-fly capability**

- Based on historical data, 95% of spares will never be used
- Impossible to know which spares will be needed
- Unanticipated system issues always appear, even after years of testing and operations

* - Based on predicted MTBFs

Image credit: Bill Cirillo (LaRC) and Andrew Owens (MIT)

ISM Objective

The AES In-space Manufacturing (ISM) project serves as Agency resource for identifying, designing, & implementing on-demand, sustainable manufacturing solutions for fabrication, maintenance, & repair during Exploration missions.

ISM EXPLORATION APPLICATIONS

Unique Agency Expertise & Leveraging of Industry

ISM TECHNOLOGY DEVELOPMENT

ISM Parts/Systems Design Database & Test Articles

Answers WHAT we need to make

- Top-down, quantitative analyses of ISM benefits to crew time, cost, mass, & reliability (w/EMC).
- Provide expertise to NASA User community on AM design optimization & materials.
- Test high-impact parts/systems to inform Exploration technology requirements (bottoms-up).
- Develop In-space Parts Design Database, processes, & materials.

Part/System Requirements, Design, Materials & Processes

ISM

'One-stop shop' for AM design, materials, & technology expertise for NASA User Community.

AM EXPERTS
MATERIAL EXPERTS
DESIGNERS

Leverage industry to meet NASA needs (i.e. Agency knowledge-base for terrestrial technology).

In-space Manufacturing provides Exploration mission benefits to cost, mass, crew time & reliability

Proactive influence during Exploration design phase required for meaningful implementation

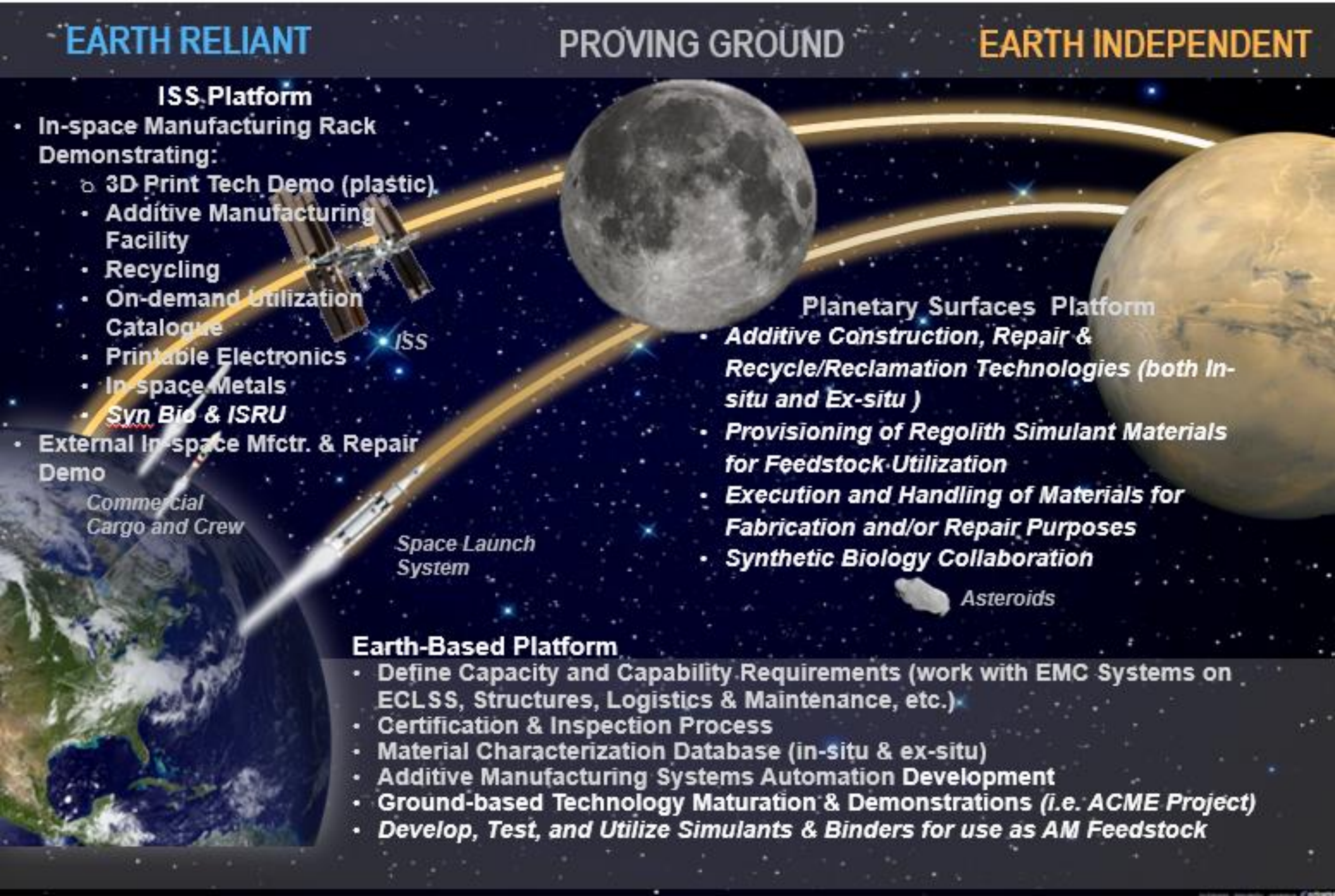
ISM Technology Development & Testing

Answers HOW we will make it

- Define NASA requirements for ISM Technologies based on ISS & EMC Applications identified (micro-g effects, performance, & operations)
- Collaborate and establish mechanisms to leverage industry to develop the technologies needed for NASA missions.
- Utilize ISS as test-bed for developing 'FabLab' to serve as springboard for cis-lunar 'proving ground' missions.

Multi-material 'FabLab' Test-bed

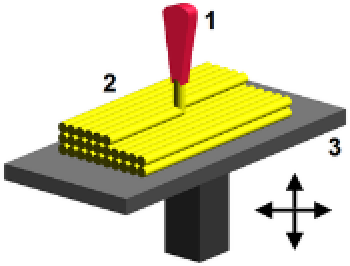
In-Space Manufacturing (ISM) Path to Exploration



The First Step: The 3D Printing in Zero G Technology Demonstration Mission

The 3DP in Zero G tech demo delivered the first 3D printer on the ISS and investigated the effects of consistent microgravity on fused deposition modeling by printing 55 specimens to date in space.

Printer inside Microgravity Science Glovebox (MSG)



Fused deposition modeling:
1) nozzle ejecting molten plastic,
2) deposited material (modeled part),
3) controlled movable table

- **Phase I prints (Nov-Dec 2014)** consisted of mostly mechanical test coupons as well as some functional tools
- **Phase II specimens (June-July 2016)** provided additional mechanical test coupons to improve statistical sampling

3D Print Specifications	
Dimensions	33 cm x 30 cm x 36 cm
Print Volume	6 cm x 12 cm x 6 cm
Mass	20 kg (w/out packing material or spares)
Power	176 W
Feedstock	ABS Plastic

Testing of Phase I and Phase II Prints

Photographic and Visual Inspection

Inspect samples for evidence of:
- Delamination between layers
- Curling or deformation of samples
- Surface voids or pores
- Damge from specimen removal

Mass Measurement

Measure mass of samples:
- Laboratory scale accurate to 0.01 mg
- Mass measurement used in gravimetric density calculation (volume derived from structured light scanning)

Structured Light Scanning

Scan external geometry of samples:
- Accurate to ± 12.7 µm
- Compare scan data CAD model to original CAD model and other specimens of the same geometry
- Measure volume from scan data
- Measure feature dimensions

Data Obtained

- Thorough documentation of sample in as-built condition

Average Sample Mass

- Geometric Accuracy
- Average Sample Volume

Average Sample Density

- Internal structure and porosity
- Densification
- Evidence of printing errors

- Mechanical Properties: UTS, E, % elongation, UCS, G

- Microstructure data
- Layer adhesion quality
- Microgravity effects on deposition

CT Scanning / X-Ray

Inspect internal tomography of samples:
- Internal voids or pores
- Measure layer thickness / bead width
- Density measurement (mean CT)
- Note any misruns or evidence of printing errors

Mechanical (Destructive) Testing

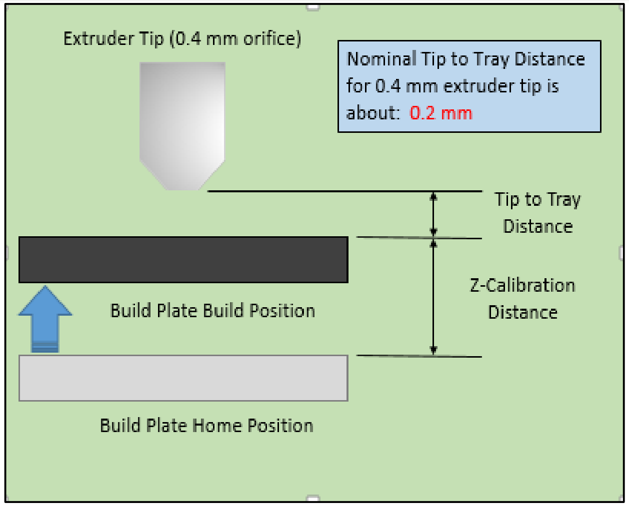
Mechanical specimens only:
- ASTM D638: Tensile Test
- ASTM D790: Flexural Test*
- ASTM D695: Compression Test

Optical / SEM Microscopy

- External features (warping, voids, protrusions, deformations)
- Internal structure
  - Filament layup
  - Voids
  - Fracture surfaces
  - Delamination

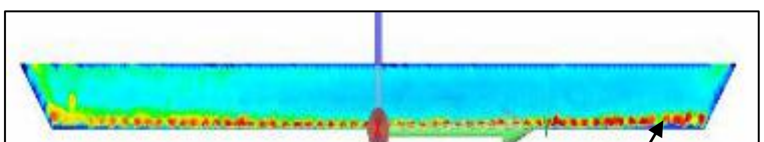
*flexure specimens not part of phase II

Key Results: The 3D Printing in Zero G Technology Demonstration Mission



Extruder standoff/tip to tray distance was varied for phase I ground and throughout phase I flight prints

Structured light scan of flight flexure specimen

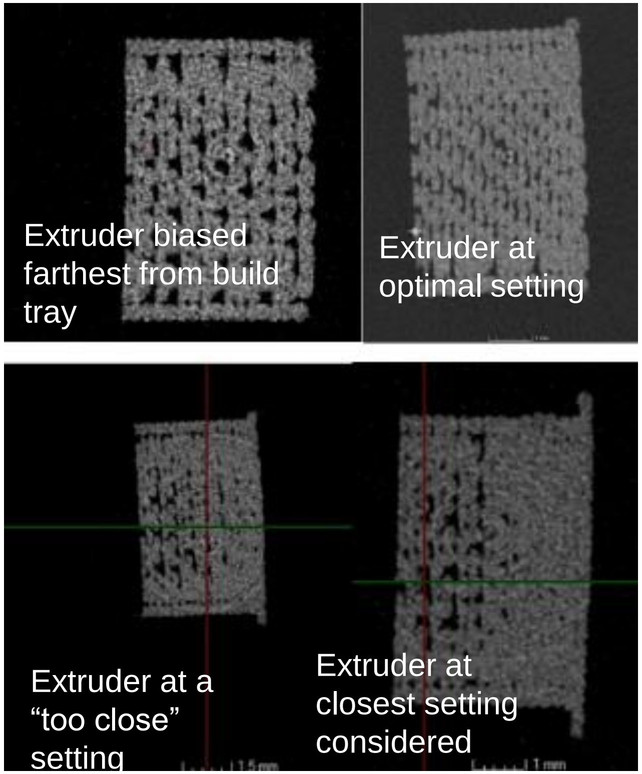


colors indicate dimensional deviation from CAD model

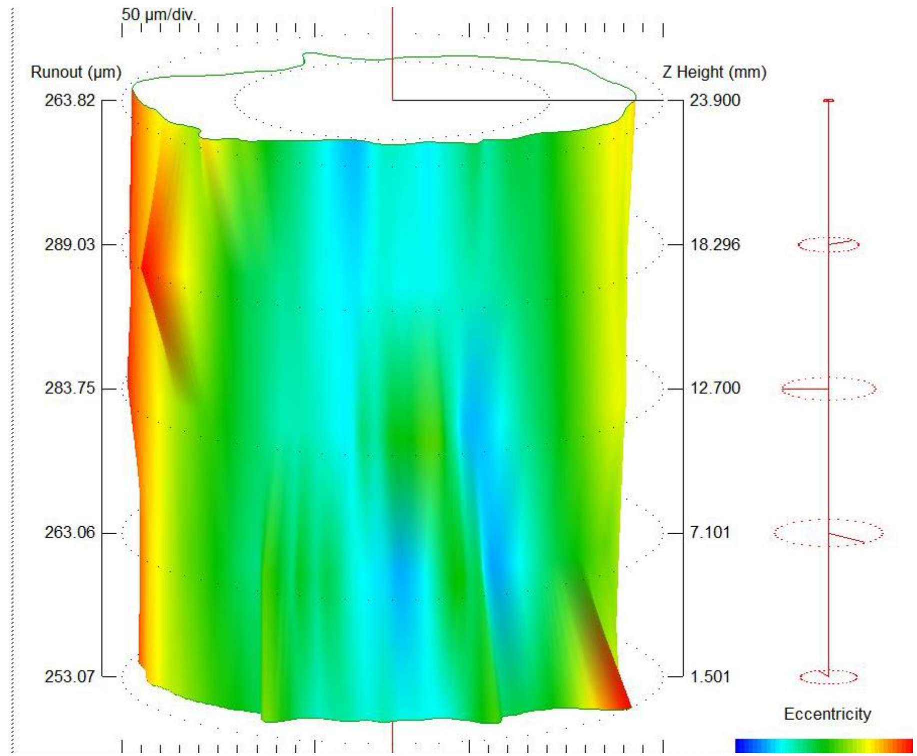
Red indicates protrusions of material created by a reduced extruder standoff distance (which may also serve to artificially strengthen the part)

- Phase I flight and ground prints (ground prints were manufactured on the 3DP unit prior to its launch to ISS) showed some differences in densification, material properties and internal structure
- Differences were determined, through SEM analysis, chemical analysis of the specimens, and a subsequent ground-based study using the identical flight back-up unit to be largely an artifact of differences in manufacturing process settings between ground and flight and also attributable to build to build variability
- Complete results published as NASA Technical Report and in queue for publication in *Rapid Prototyping Journal*
- Follow-on ground-based study " A Ground Based Study on Extruder Standoff Distance for the 3D Printing in Zero G Technology Demonstration Mission" will be available on NASA Tech Reports Server in June 2017

Key Results: The 3D Printing in Zero G Technology Demonstration Mission (ground-based study)



CT cross-section images show evolution of tensile specimen structure with decreasing extruder standoff distance (images from reference , a ground-based study using the flight-back up unit). Bottom half of the specimen becomes denser and protrusions form at base of specimen as extruder standoff distance is decreased.



Results of cylinder mapping of compression cylinder from ground based study of extruder standoff distance using the flight backup unit. Off-nominal conditions for the extruder tip biased in either direction result in an increase in cylindricity. The greatest radial separation is observed for the closest extruder setting.

Key Results: The 3D Printing in Zero G Technology Demonstration Mission (Phase II)

- For phase II operations, 25 specimens (tensile and compression) were built at an optimal extruder standoff distance.
- For the last 9 prints in the 34 specimen print matrix, extruder standoff distance was decreased intentionally to mimic the manufacturing process conditions for the phase I flight prints.
- Complete phase II data will be published on the NASA Technical Reports Server in late summer 2017.

ISM Utilization and the Additive Manufacturing Facility (AMF): Functional Parts

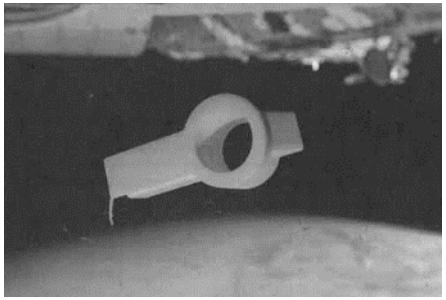
The Made in Space Additive Manufacturing Facility (AMF)

- Additive Manufacturing Facility (AMF) is the follow-on printer developed by Made in Space, Inc.
- AMF is a commercial, multi-user facility capable of printing ABS, ULTEM, and HDPE.
- To date, NASA has printed several functional parts for ISS using AMF

SPHERES Tow Hitch: SPHERES consists of 3 free-flying satellites on-board ISS. Tow hitch joins two of the SPHERES satellites together during flight. Printed 2/21/17.

REM Shield Enclosure: Enclosure for radiation monitors inside Bigelow Expandable Activity Module (BEAM). Printed 3/20/17 (1 of 3).

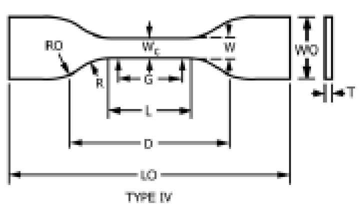
Antenna Feed Horn: collaboration between NASA Chief Scientist & Chief Technologist for Space Communications and Navigation, ISM & Sciperio, Inc. Printed 3/9/17 and returned on SpaceX-10 3/20/17.



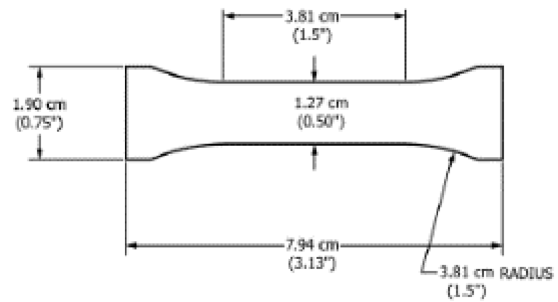
OGS Adapter: adapter attaches over the OGS air outlet and fixtures the velocicalc probe in the optimal location to obtain a consistent and accurate reading of airflow through the port. 7/19/2016.

ISM Utilization and the Additive Manufacturing Facility (AMF): Materials Characterization

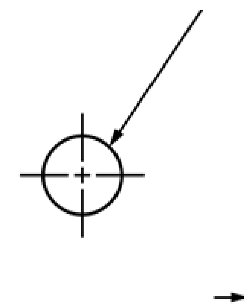
- To inform continued utilization of AMF by NASA, a materials characterization plan was developed and is now on contract with Made in Space
- Initial plan is to develop characteristic properties for ABS produced by AMF, but plan is extensible to other materials
- Testing methodology similar to composites. Test coupons are machined from printed panels (***4 mm thickness***).
- Panels printed at 0 (for tension and compression), 90, and +/-45 layup patterns.



Type IV tensile specimen from ASTM D638

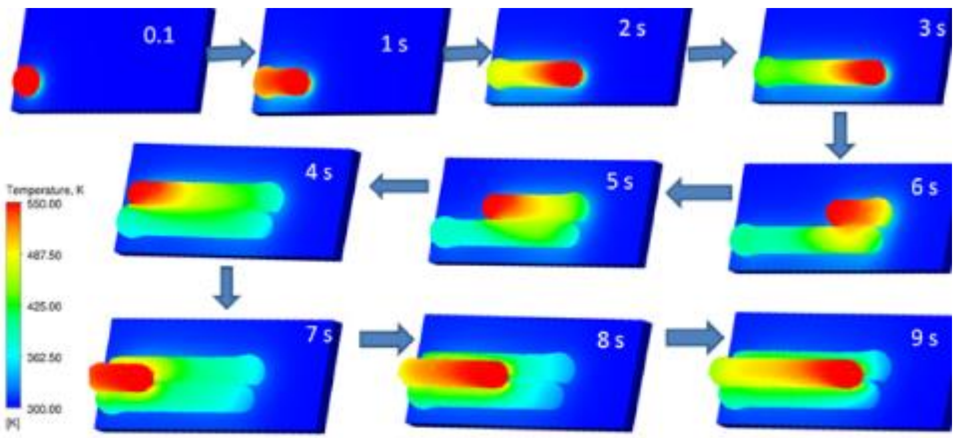


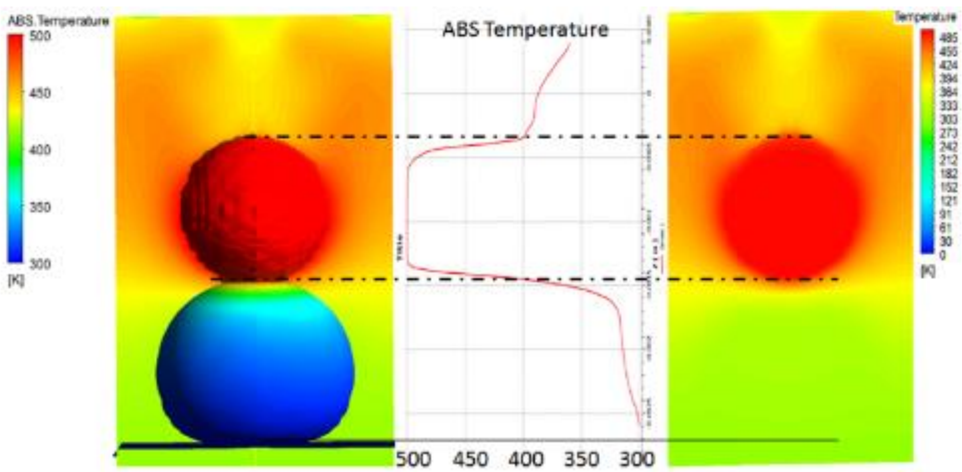
Thin-type compression specimen from ASTM D695. Requires support jig.



Flatwise tension from ASTM C297. Used to measure tensile strength in the through thickness of the specimen.

Modeling work on FDM (NASA Ames Research Center)





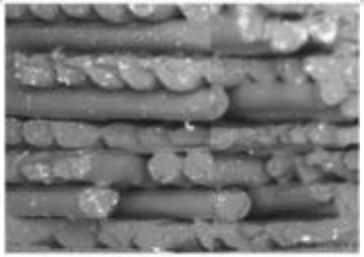
Slide credit: Dr. Dogan Timucin, Ames Research Center

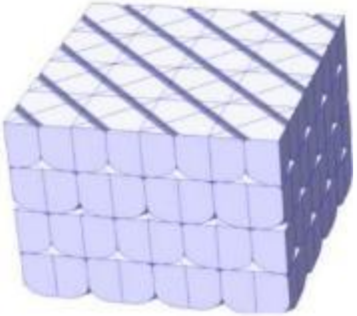
- Objective is to model FDM process in space (initially for ABS) and predict structural properties of the manufactured parts
- Use physics based analysis of FDM to determine what physics phenomena may be distinct in space-based manufacturing
- Developed FE model in ANSYS CFX for coupled fluid flow and heat conduction problem associated with filament extrusion and deposition
  - Uses ABS parameters available in the literature
- Performed qualitative analysis of inter-diffusion between two molten roads based on polymer reputation theory for long-chain molecules
- Concluded that the reputation time is much smaller than the time to cool down to glass transition temperature
  - Filaments can be assumed perfectly welded
- ***No significant changes in road shape, filament temperature distribution, die swell, or evolution of temperature profile noted in modeling and simulation due to variation in gravity parameter***

Modeling work on FDM (NASA Ames Research Center)

Structural Modeling of Macroscopic FDM parts

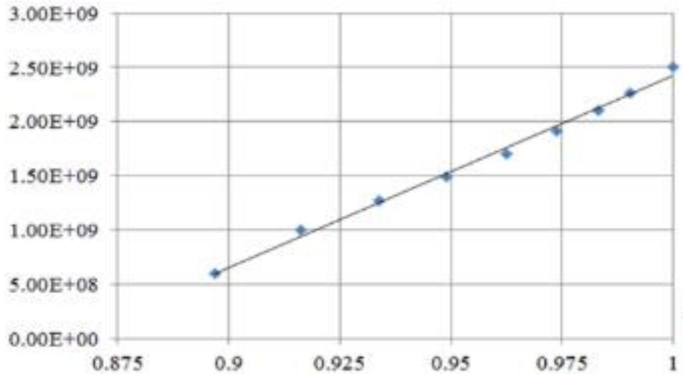
- Modeled FDM parts as a composite cellular structure with known microstructure (as determined from the deposition process model)
- Effective structural parameters of the part were studied analytically based on classical homogenization and laminate theories
- Developed a finite-element model in ABAQUS to estimate the elastic moduli of representative volume elements or unit cells in order to verify analytical models
- Moduli were simulated for different layups, raster orientations, air gap distribution as a function of volume void fraction
- The part strength was estimated using the Tsai-Wu failure criterion

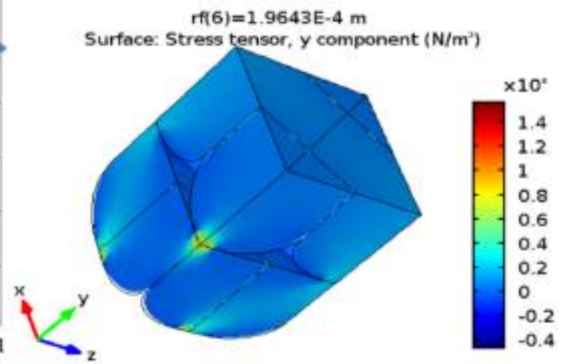




representative volume element

elastic modulus as a function of void fraction



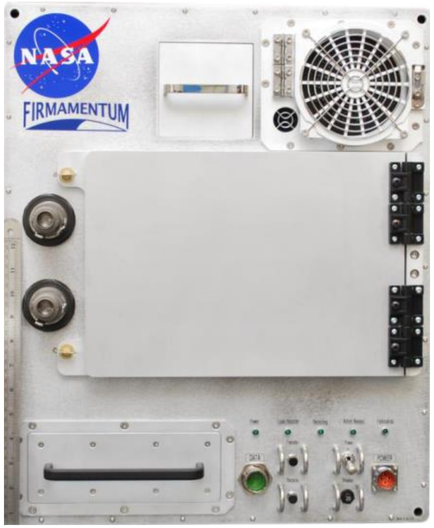


unit cell FE simulation

Slide credit: Dr. Dogan Timucin, Ames Research Center

ReFabricator from Tethers Unlimited, Inc.: Closing the Manufacturing Loop

- Technology Demonstration Mission payload conducted under a phase III SBIR with Tethers Unlimited, Inc.
- Refabricator demonstrates feasibility of plastic recycling in a microgravity environment for long duration missions
- Refabricator is an integrated 3D printer (FDM) and recycler
  - Recycles 3D printed plastic into filament feedstock through the Positrusion process
- Environmental testing of engineering test unit completed at MSFC in April
  - Payload CDR completed in mid-June
  - Operational on ISS in 2018



Refabricator ETU

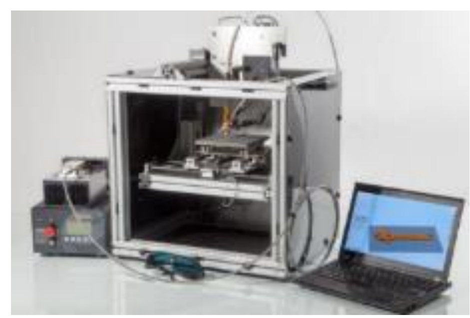
Other Small Business Innovative Research (SBIR) Activities

- **Tethers Unlimited, Inc.:** Customizable, Recyclable ISS Packaging (CRISSP)
- **Cornerstone Research Group, Inc. (CRG):** Reversible Copolymer Materials for FDM 3D Printing of Non-Standard Plastics
- **Tethers Unlimited, In**c.: ERASMUS Food & Medical Grade Integrated Sterilizer, 3D Printer, and Recycler
- **Techshot, Inc.:** Sintered Inductive Metal Printer with Laser Exposure (SIMPLE), a novel in-space metals manufacturing technology

- Five new SBIRs funded under the subtopics ***In-Space Manufacturing of Precision Parts*** and ***In-Space Manufacturing of Electronics and Avionics***

CRISSP (image from Tethers Unlimited)

ERASMUS (image from Tethers Unlimited)



SIMPLE (image from Techshot, Inc.)

FDM prints using reclaimed anti-static bagging film with reversible cross-linking additive (image from Cornerstone Research Group)

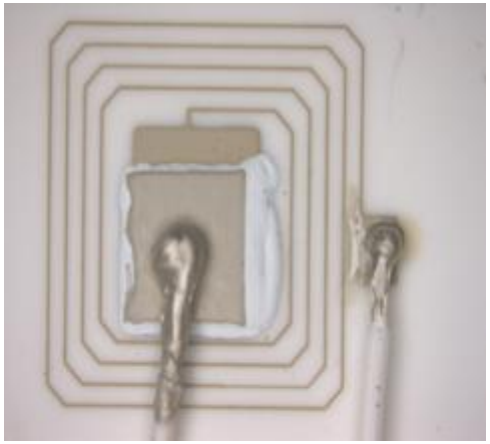
Ground-based work on additive electronics

- evaluating technologies to enable multi-material, on-demand digital manufacturing of components for sustainable exploration missions

- Development of wireless sensor archetype
  - Printed RLC circuit with coupled antenna
  - Capacitive sensing element in circuit is pressure, temperature, or otherwise environmentally sensitive material
  - Sensing material also developed in-house at MSFC

- Design of pressure switch for urine processor assembly (UPA)
  - Existing pressure switch has had several failures due to manufacturing flaw in metal diaphragm
  - In additive design, switching is accomplished via a pressure sensitive material turning a transistor on when the system exceeds a certain pressure

- Work on miniaturization and adaptation of printable electronics for microgravity environment will continue through two contracts awarded under SBIR subtopic In-Space Manufacturing of Electronics and Avionics

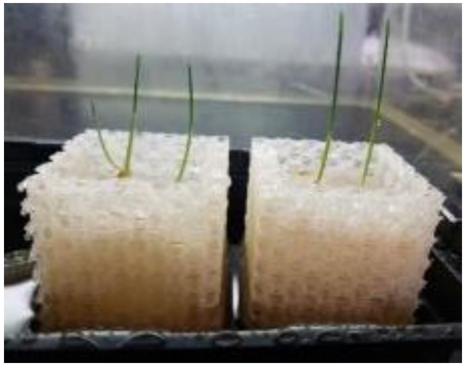


Printed wireless humidity sensor (wires attached for characterization purposes)

nScrypt multimaterial printer

3D Printing with Biologically Derived Materials

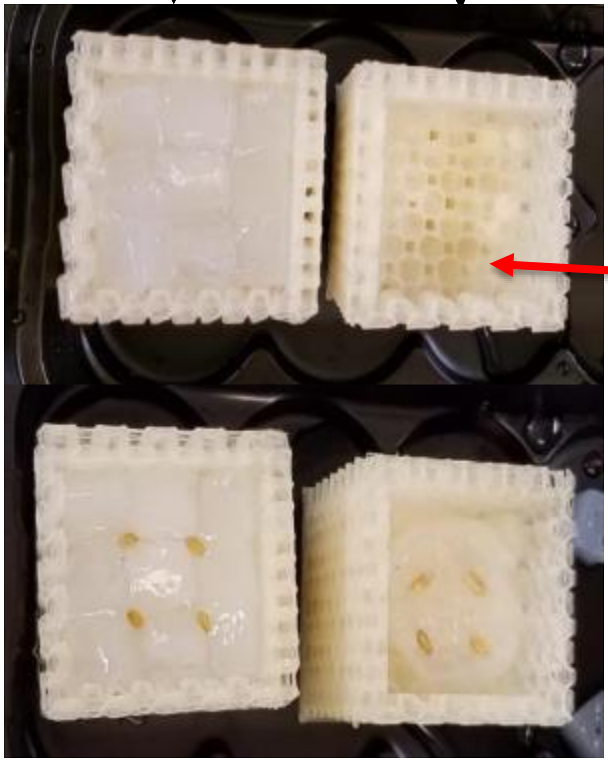
- Use biologically derived filament materials and/or materials from inedible plant mass to create 3D printed substrate blocks for plant growth
- Collaborative activity between VEGGIE project/payload at Kennedy Space Center, Synthetic Biology team at Ames Research Center, and In-space Manufacturing team at NASA Marshall



COTS microbial cellulose

ARC microbial cellulose

Microbial cellulose used as seed germinating platform



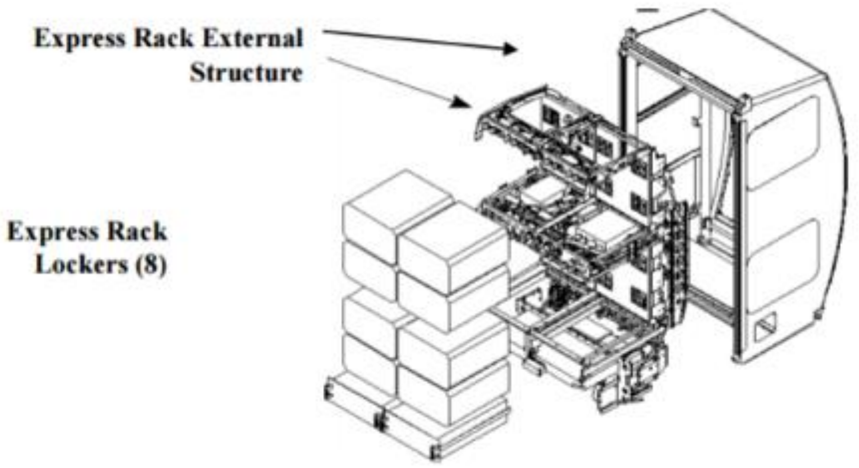
Moisture Retainer
-Starch polymer

3D Printed plant growth blocks from MSFC (PLA/PHA)

Seeds allowed to germinate for 3 days

The Multimaterial Fabrication Laboratory for ISS ("FabLab")

Typical EXPRESS Rack structure



Power consumption for entire rack is limited to 2000 W

Payload mass limit for rack is less than 576 lbm

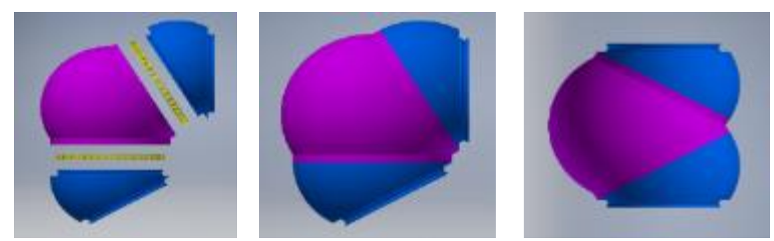
- NASA is seeking proposals to provide a feasible design and demonstration of a first-generation In-space Manufacturing Fabrication Laboratory for demonstration on the ISS
- Minimum target capabilities include:
    - Manufacturing of metallic components
    - Meet ISS EXPRESS Rack constraints for power and volume
    - Limit crew time
    - Incorporate remote and autonomous verification and validation of parts
- Proposals due August 2, 2017
- Opportunity posted on Federal Business Opportunities Website: www.fbo.gov/index?s=opportunity&mode=form&tab=core&id=8a6ebb526d8bf8fb9c6361cb8b50c1f8

Student Projects

- Future Engineers, collaboration between NASA and American Society of Mechanical Engineers challenges K-12 students to design space hardware that can be 3D printed: www.futureengineers.org
  - Think Outside the Box Challenge (ended October 2016)
  - Mars Medical Challenge (ended March 2017)
- Senior design project with Vanderbilt University (2016-2017 academic year)
  - Design of a 3D printed parametric tool kit and dynamic user interface for crew use
  - Feasibility study of 3D printing of lattice casts (alternative to SAM splint procedure and traditional casts)
- NASA XHab university projects
  - Student teams apply NASA systems engineering practices to develop hardware
  - 2016-2017 projects with University of Connecticut and University of Maryland

Vanderbilt University Senior Design Pictured: 3D printed lattice cast segment

University of Connecticut XHab: Design of an integrated recycler and printer for ISS



University of Maryland: 3D Printing of Spacesuit components (pictured: 3-element wedge for elbow)

Collaborators

- Niki Werkheiser, In-Space Manufacturing Project Manager
- Mardi Wilkerson, Deputy Project Manager, In-Space Manufacturing
- Dr. Raymond “Corky” Clinton, Deputy Manager, NASA MSFC Science and Technology Office
- Zach Jones, Technology Discipline Lead Engineer for ISM
- Howard Soohoo, Chief Engineer for ISM
- Dr. Frank Ledbetter, Senior Technical Advisor for In-Space Manufacturing
- Dr. Dogan Timucin and Dr. Kevin Wheeler, Ames Research Center
- Steve Newton, Recycler Task Lead
- Personnel who worked on testing and analysis of materials:
    - Dr. Terry Rolin (CT)
    - Dr. Ron Beshears (CT)
    - Ellen Rabenberg (SEM)
    - Cameron Bosley (mechanical test)
    - Dr. Richard Grugel (SEM)
    - Lewis “Chip” Moore (surface metrology)

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